Environmental and Safety Issues Associated with a 30-GeV Proton Synchrotron

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This paper summarizes activation of materials, radioactive waste, sky-shine radiation, groundwater radioactivity, airborne radioactivity, beam faults, exposure of staff, and the environmental performance indicator for a high-energy synchrotron-accelerator-complex on Long Island, New York. Groundwater contamination is a particularly sensitive area of concern. The Laboratory site is located over an EPA designated sole-source aquifer system and there is significant public concern over ^{3}H in on-site groundwater. This paper is intended to give you information about the environmental impacts of one portion of Laboratory operations: the Alternating Gradient Synchrotron (AGS) complex of accelerators that deliver protons and heavy-ions to the high-energy physics and nuclear physics communities.

INTRODUCTION

Understanding the magnitude of radioactivity and ionizing radiation produced by a high-energy proton synchrotron is essential for environmentally sound operation. A proton synchrotron, however, is an experimental machine and parameters for long-term operations are often only vaguely specified at the start of operations. Many improvements or unusual modes of operation occurred over the last 38 years. Generally, an environmental and safety envelope is specified and operations of the complex occur within its bounds. Given the inherent uncertainty in real-life accelerator operations, any long-term extrapolation of radioactivity or radiation level to another accelerator is likely to be subjective. It is hoped, however, that the issues presented here provide the reader with a reasonably quantitative assessment of the impact of high-energy proton synchrotrons.

At this time, the AGS Department has a high-energy physics program to look for physics beyond the Standard Model. In the area of nuclear physics, the heavy-ion physics program is searching for evidence of the quark-gluon plasma and the production of strangeness enriched matter. This part of the experimental program is the natural lead in to the next generation of experiments to be performed at the Relativistic Heavy Ion Collider, which is nearing completion. In the area of health effects, heavy ions of the type encountered in space travel are studied. Polarized-proton experiments are also being developed.

The operational complex is made up of the Linac, the Tandem Van De Graaff, the Booster synchrotron, the AGS synchrotron, the slow-extracted-beam experimental area, and the fast-extracted-beam experimental area. The Linac is a linear accelerator and it accelerates H^- ions to 200 MeV. The BNL Medical Department uses most of the Linac beam in its Brookhaven Linac Isotopes Producer (BLIP) for the production of radiopharmaceuticals. A small fraction of the total Linac beam is sent to the Booster synchrotron. At the Booster, electrons are stripped off and the proton beam is accelerated to about 1.9 GeV. It is injected into the AGS synchrotron where acceleration up to 30 GeV occurs. At this time, the output from AGS is $6x10^{13}$ protons every 2 to 3 seconds at 24 GeV. Essentially all induced radioactivity at the complex is attributed to proton operations.

The AGS accelerates heavy ions at the intensity of about 10^{11} nucleons every 3 seconds. The ions reaching the AGS start at the Tandem van De Graaff where they reach about 1 MeV per nucleon. These heavy ions are injected into the Booster synchrotron, and then AGS. The final heavy-ion energy is about 11 GeV per nucleon for Au ions.

At this time, five slow-extracted-beam targets and one fast-extracted-beam target each receive from $5x10^{18}$ to $1.5x10^{19}$ protons y^{-1} at 24 GeV from AGS. The BLIP uses $3x10^{21}$ 200 MeV protons y^{-1}. Booster synchrotron losses are about $2x10^{18}$ protons y^{-1} at 1-GeV effective energy, and at AGS about $3x10^{18}$ at 8-GeV effective energy.

During transport through many hundreds of meters of tunnel and accelerators, a small percentage of the beam is lost. This errant beam is shielded with up to 7-m thick earth-roofs and 20-m thick earth-sides. Most accelerated particles end at targets inside heavily shielded target-caves with 3-m thick high-density-concrete walls. About half the proton beam interacts in a target, with the remainder going to the next target downstream or directly to a beam stop. Errant beams interact in items such as magnets, concrete, iron, earth, vacuum pipes and cables. The result is that accelerators and transport tunnels have localized areas of residual radioactivity in addition to that at target caves. A massive collimator captures beam diverging from the first of two targets placed in tandem in one of the beam-lines. This significantly reduces widespread activation of downstream magnets and magnet cooling-water.

Target caves tend to be the locations where the highest level of residual gamma-radiation is measured. Target

caves contain items similar to items found in transport tunnels; in addition, they shield the targets, which are several 100 g of Pt or Cu, or several kilograms of Ni. The uncollided protons escaping the final target end in iron and concrete beam stops that are up to 50 meters long.

ACTIVATION OF MATERIALS

When a high-energy proton interacts with a nucleus, many secondary particles are emitted which have a high enough energy to produce further particles when they interact, thus creating a nuclear particle cascade. A range of secondary particles (p, n, π) are produced, and they in turn produce radionuclides through inelastic reactions; e.g., ^{3}H, ^{7}Be, ^{22}Na, and ^{60}Co. A summary of the environmentally important radionuclides is shown in Table 1.

TABLE 1. Environmentally Important Radionuclides Produced In Earth, Air, Water and Beam-line Components

Earth	Air	Water	Magnets / Vacuum Pipe (Fe, Cu, Al)
^{3}H, ^{7}Be, ^{22}Na	^{3}H, ^{7}Be, ^{11}C, ^{13}N, ^{14}O, ^{15}O, ^{41}Ar	^{3}H, ^{7}Be, ^{11}C, ^{13}N, ^{14}O, ^{15}O	^{22}Na, ^{60}Co

The materials used in the construction of the AGS and Booster synchrotron are limited in number, the most important being Fe, Cu, Al, concrete, oil and plastic. Materials are not used in pure form. That is, they have dissimilar metals at weld joints, or they are alloyed with other metals such as Ni or Co. Materials consist of naturally occurring stable isotopes of the element. Thus, irradiation with high-energy hadrons produces different radionuclides in any given accelerator item, however, almost every item has some level of residual ^{60}Co activity.

It is important to know that induced radioactivity is deeply entrained in materials due to the penetrating ability of the hadrons. It is not readily dispersible to the environment, even in a fire.

Measurements indicate the gamma-activity per unit mass ranges from 1 to 5 nCi g^{-1} (40 to 200 Bq g^{-1}) after several months of decay. The predominant nuclide is ^{60}Co, which has a 5.3-year half-life. Long-lived pure β-emitters are also present in materials, but are difficult to detect. An upper estimate of activity relative to the measured ^{60}Co activity is based on the relative production cross-section, half-life and abundance of different elements in different materials. It is estimated that ^{3}H and ^{63}Ni are present at 1 nCi g^{-1} (40 Bq g^{-1}) or less, ^{14}C at 50 pCi g^{-1} (2 Bq g^{-1}) or less, ^{59}Ni at 1 pCi g^{-1} (0.04 Bq g^{-1}) or less, ^{93}Mo at 0.4 pCi g^{-1} (0.01 Bq g^{-1}) or less, and ^{151}Sm at 10 aCi g^{-1} (0.0004 Bq g^{-1}) or less.

RADIOACTIVE WASTE

The AGS generates 100 m^{3} of solid low-level radioactive waste per year. Most items are re-used year after year. The cost of burying low-level radioactive waste is about $5000 m^{-3}. The cost includes labor associated with handling and packing waste, transport, container and burial charges.

Concerning decommissioning, activated shielding is re-used in accelerator facilities. Large shield blocks shipped across the United States from decommissioned accelerators are less expensive than new shield blocks. In addition, allowing 50 or more years for ^{60}Co to decay reduces gamma radiation from activation products below background.

Liquid waste comes about by regeneration of ion-exchange resins. The regeneration process creates 50,000 L of wastewater per year. The principle radionuclides are ^{7}Be and ^{3}H. The cost of treatment is $3 L^{-1}, which includes the cost of removing dissolved metals and evaporating ^{3}H-laden water. The AGS is eliminating regeneration and instead disposing of spent resin as solid radioactive waste. The volume of spent resin at AGS each year is about 4 m^{3}.

SKY-SHINE RADIATION

Radiation that extends several hundred meters from the AGS is termed sky-shine. It is due to neutrons escaping through thin parts of accelerator roof-shields. Roof shields are inaccessible during operations. The upward neutrons scatter in air above the complex, and mixed gamma-neutron radiation arrives back at ground level.

Sky-shine levels at AGS fall off rapidly and are less than the Laboratory guides for annual exposure of 25 mrem (0.25 mSv) on-site and 5 mrem (0.05 mSv) off-site. The on-site Laboratory guide applies to the nearest non-AGS facility. Sky-shine levels are low due to limiting the radiation coming directly through the shield, which dominates the shield requirements.

The Laboratory does not measure low-level neutron dose directly; however, many studies at AGS show the ratio between neutron and gamma dose-equivalent to be 1.3. Off-site gamma dose-equivalent is measured with thermoluminescent dosimeters. Radiation measurements near the site boundary at 1400 m are consistent with natural background, about 63 mrem y^{-1} (0.63 mSv y^{-1}), and do not appear to be influenced by AGS operations. The annual onsite dose from sky-shine was 7 mrem (0.07 mSv) to the nearest non-AGS worker at 200 m in 1995, when slow-extracted-beam high-intensity operation peaked at 1x10^{20} protons at 24 GeV.

GROUNDWATER RADIOACTIVITY

The AGS designs facilities to protect groundwater. Two design principles are used to eliminate environmental impact. The use of roofs or barrier-like concrete pads is the first design principle and it eliminates the penetration of rainwater through potentially activated soil. A limit on the radioactivity concentration in soil moisture, should rainwater penetration occur, is the second principle. The second principle is satisfied by an appropriate thickness of concrete or iron between the beam loss-point and the soil.

The limiting activity concentration is the New York State Drinking Water Standard (DWS). The DWS corresponds to 4 mrem y^{-1} (0.04 mSv y^{-1}) if an individual drinks radioactive water year-round. Until recently, the AGS used the DOE ALARA (As Low As Reasonably Achievable) Design Guide, which is 500 mrem y^{-1} (5 mSv y^{-1}). Decay time and dispersion due to groundwater flow were used to show the ALARA Guide results in less than the DWS should an inadvertent effluent reach the site boundary. However, the public has recently shown concern for on-site contamination above the DWS.

Radioactivity produced in soil can be transferred by rainwater to groundwater as it percolates downward to the water table. The water table is typically 10 m below the surface. All ^{3}H produced in soil can be transferred but only a few % of ^{22}Na has been observed to be leached from activated soil. The radionuclides ^{55}Fe, ^{45}Ca, ^{41}Ca, ^{54}Mn, ^{49}V, ^{35}S, ^{7}Be, ^{14}C are also produced in soil but these nuclides appear to be retarded in movement to groundwater. Only traces of ^{22}Na and ^{3}H, one order of magnitude less than the DWS, are detected in on-site groundwater samples taken near AGS facilities. On the other hand, samples of groundwater taken in March 1998 near the BLIP facility showed ^{3}H and ^{22}Na concentrations approaching the DWS. A 13-cm thick barrier-like concrete pad was placed over the BLIP target area, and nearby groundwater measurements have since returned to trace levels.

For clarification, the Medical Department's BLIP facility uses an earth beam-stop, whereas the AGS Department uses concrete and iron for beam-stops. The total soil activity of ^{22}Na at BLIP for each year of operation is estimated to be about 10 Ci ($4x10^{11}$ Bq), and ^{3}H about 2 Ci ($7x10^{10}$ Bq). On-the-other-hand, the estimates of activity in soil near targets in the AGS slow-extracted-beam areas are $3x10^{-3}$ Ci ($1x10^{8}$ Bq) for ^{22}Na and $1x10^{-3}$ Ci ($4x10^{7}$ Bq) for ^{3}H for each target for each year of operation.

At the site boundary, hypothetical contaminated groundwater becomes less radioactive in transit due to radioactive decay. Contaminant dispersion-models show a reduction in activity concentration of five orders of magnitude for ^{3}H in transit through 1400 m of typical Long Island soil. A reduction of seven orders of magnitude for ^{22}Na activity concentration may be similarly computed.

At AGS, about 20 activated cooling-water systems are distributed throughout the magnet enclosures. A network of floor drains collects leaks. Activated water inadvertently entering the floor-drain system is conducted to the sanitary-sewer system or is collected in sumps. The sanitary-sewer system ejects water to a river that is partly groundwater. In cases where water is collected in sumps, automatic pumps are turned off and sumps are alarmed. Sump water is collected in tankers and sampled prior to disposal.

Activated cooling-water systems contain the radionuclides indicated in Table 1, but ^{3}H is the only nuclide of environmental significance. About 300,000 L of cooling water is contained in the activated closed-looped cooling systems at AGS. Total ^{3}H activity is about 30 mCi ($1x10^{9}$ Bq). Optimizing beam transport through beam-line components minimizes activation. Levels of ^{3}H activity-concentration range from $2x10^{-5}$ to $5x10^{-3}$ μCi cm^{-3} ($7x10^{2}$ to $2x10^{5}$ Bq L^{-1}). The DWS is $2x10^{-5}$ μCi cm^{-3} ($7x10^{2}$ Bq L^{-1}). Because discharge to sanitary above the DWS is not allowed by the Laboratory, activated water is retained in tankers during maintenance and returned to cooling-systems whenever possible. However, 5000 to 8000 L y^{-1} cannot be re-used. Additionally, AGS collects activated condensate from accelerator air-conditioning systems. Condensate contains ^{3}H due to activation of air. Unusable radioactive water collected in tankers is either evaporated or released in a controlled manner to the sanitary system.

Some activated cooling-water systems in the experimental areas are not in closed-loops. Activated water in these systems is connected directly to cooling towers, which results in an airborne emission of the short-lived radio-gases indicated in Table 1. Water in these towers is continuously made-up in order to compensate for evaporative losses. Thus, buildup of measurable amounts of ^{3}H in cooling-tower water does not occur.

The frequency of spills from cooling-water systems is minimized by choosing system components suited to the differential pressures involved. A hose or pipe break or a seal failure occurs about once every 4 years at a level that releases more than 400 L of activated water. In order to reduce environmental impact, cooling-system makeup water is monitored by computer and alarmed in the Main Control Room, which is manned round-the-clock during operations periods. Pumps automatically turn-off when a leak is detected. Operators are trained to respond to alarms and are trained to minimize the release should a leak occur.

AIRBORNE RADIOACTIVITY

By design, AGS airborne emissions from the accelerators are not allowed during normal operations. The EPA limit is 10 mrem y^{-1} (0.1 mSv y^{-1}) at the site boundary from airborne radioactivity. Linac, Booster and AGS work fine with during operations with re-circulating air-conditioning systems. In the experimental areas, trace amounts of short-lived airborne radioactivity are observed near target-cave gates although there is no air-moving system. Activation of air in experimental beam lines is minimized by ensuring the path of beams in air is minimized. This is done by keeping the beam inside vacuum lines or by using helium-filled bags in the air path.

Typical gross-beta airborne-radioactivity concentration near target-cave gates is $1x10^{-8}$ μCi cm^{-3} (0.4 Bq L^{-1}) or less. A total immersion dose-rate from airborne radioactivity near a gate is estimated to be about 0.2 mrem h^{-1} (0.002 mSv h^{-1}) with $2x10^{13}$ p s^{-1} on target. Most of the dose rate is attributed to ^{15}O, which has a 2.1 minute half-life, although other radionuclides indicated in Table 1 are present. Traces of short-lived ^{39}Cl and ^{38}Cl are also observed. These two gaseous radionuclides emanate from targets. The high-intensity fast-extracted-beam target has secondary containment to trap Cl spallation-products. Gross-beta airborne-radioactivity is not measurable more

than a few meters beyond the target-cave gates, and is not considered to have significant environmental impact.

Activated water in cooling-towers in experimental areas is exposed to air as it moves about 10 m above the ground through a tower. The short-lived gamma-emitting dissolved radio-gases ^{14}O, ^{15}O, ^{13}N and ^{11}C are present, and measurements indicate a transfer to air of about 0.04%. However, meteorological models and measurements show radio-gas emissions to be indistinguishable from background at the site boundary. Models show that dose estimates from this source are 5 to 7 orders of magnitude below the EPA limit of 10 mrem (0.1 mSv).

BEAM FAULTS

Fault levels in accessible areas are limited to no more than 20 mrem (0.2 mSv) per event. Faults occur if beam is not steered correctly or if magnet power-supplies fail. In most cases, passive shielding or other barriers provide protection. In some accessible areas, dose rates are allowed up to 7 rem h^{-1} (0.07 Sv h^{-1}) in a fault. Area radiation-monitors are employed and they interlock at 2 mrem h^{-1} (0.02 mSv h^{-1}). Faults last no more than 9 seconds before interlock occurs, which limits the integrated exposure to less than 20 mrem (0.2 mSv) per event. These events are logged by computer and investigated. These events occur several times per year and there is no significant safety or environmental impact.

EXPOSURE OF STAFF AND USERS

Persons are not allowed an exposure greater than 1000 mrem y^{-1} (10 mSv y^{-1}) at AGS. About 600 staff and users are present as radiation workers each month. Staff receives an annual average dose of about 100 mrem y^{-1} (1 mSv y^{-1}), which is about one-third of natural-background radiation on Long Island. Proton-beam users receive about 40 mrem y^{-1} (0.4 mSv y^{-1}). AGS has reduced collective dose from 650 person-rem (6.5 person-Sv) in 1973 to about 50 person-rem (0.5 person-Sv) in 1998, while at the same time increased proton intensity several orders of magnitude. Most success in reducing collective dose was achieved by designing systems that are less sensitive to radiation damage. This has reduced repair work in high-radiation areas.

ENVIRONMENTAL PERFORMANCE

The AGS tracks performance in terms of reportable environmental occurrences and the declining trend is shown in Fig. 1. Typical events range from a leak of 4 L of oil at an outdoor transformer-yard to a leak of chlorine gas from a 70-kg cylinder. The largest spill was 3000 L of anti-freeze from a portable-cooling unit, which was cleaned up. In the last 8 years, only two events involved a spill of activated-cooling water: 2000 L in 1995 from a leak in a hold-up tanker, and 400 L in 1998 from a freeze-cracked pipe in a heat-exchanger. In both cases, ^{3}H was not detected in the $4x10^{7}$ L recharge basin where the water ended up. Both events involved ^{3}H at concentrations initially above the DWS. The 1995 event went unnoticed by the public. The 1998 event resulted in negative articles to appear in New York's Newsday. Suffolk County Department of Health subsequently reviewed AGS systems and recommended secondary containment for pipes and continuous monitoring for leaks. AGS is planning to implement improvements in the next few years, as funding becomes available.

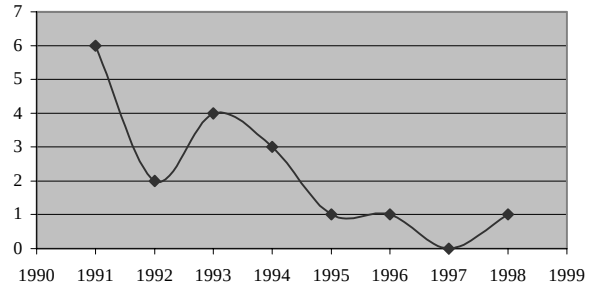

Figure 1. Number of Environmental Occurrences at AGS

DISCUSSIONS AND CONCLUSIONS

Based on experience and analysis, there is no potential for significant off-site impact on the environment from accelerator operations. However, the Laboratory site is located over an EPA designated sole-source aquifer and there is public concern over ^{3}H in on-site groundwater. Thus, the Laboratory is upgrading the groundwater monitoring program and is hiring a 4-person staff of environmental engineers to help implement pollution-prevention programs. In FY99, 34 monitoring wells will be added to the 9 monitoring wells around AGS, and one environmental engineer will be assigned to the AGS complex. The AGS is upgrading activated water systems with secondary containment, and the Laboratory is actively seeking greater public participation in environmental issues.

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